Phase Transition of Newborn Neutron Stars as a Link of Supernova/Gamma-Ray Burst Connection

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ABSTRACT

We here present a natural explanation of the puzzling connection between supernova and gamma-ray burst. An asymmetric supernova explosion produces a mildly relativistic jet and leaves a preferred baryon-free funnel for the fireball formed few days later by the conversion of the newborn neutron star to a strange star, or/and from the differentially rotating strange star. The fireball can be accelerated to ultra-relativistic velocity ($\Gamma_0 > 100$) due to the very low baryon contamination of the strange star and subsequently produce the γ-ray burst. Most of the conversion energy will finally turn into the kinetic energy of the supernova ejecta, leading to a very luminous supernova similar to SN1998bw. We also show that the late rise in the radio light curve of GRB980425/SN1998bw can be attributed to the energy input from the resultant strange star.

subject headings: gamma-ray: bursts — supernova: general — stars: neutron — elementary particles

1. INTRODUCTION

About a year ago, Galama et al. (1998) reported the detection of a very luminous Type Ic supernova (SN) SN1998bw in the error box of GRB980425. The estimated chance probability of the coincidence is 10^{-4}, suggesting a connection between these two events. From the radio observations of GRB980425/SN1998bw, Kulkarni et al. (1998) concluded that there exists a relativistic shock (bulk Lorentz factor $\gamma \equiv (1-\beta^2)^{-1/2} \geq 2$) even 4 days after the supernova explosion. Li & Chevalier (1999) modelled the radio light curves and inferred that the late rise observed at days 20-40 is the result of energy input from a central engine. These both strengthen the link between SN1998bw and GRB980425. More recently, Bloom et al. (1999) and Reichart (1999) revisited GRB980326 and GRB970228, respectively, and found the evidence for a supernova in the light curve and late spectral energy distribution of the afterglow. Galama et al. (1999) reached the same conclusion for GRB970228 by the reanalysis of its optical and near-infrared afterglow. It appears that there exists a subclass of gamma-ray bursts (GRBs) associated with supernovae, or supernova-GRBs (SN-GRBs; Bloom et al. 1998).

More than a decade years ago, Karovska et al.(1987) and Matcher et al.(1987) reported the observations of a "mystery spot" near SN1987A. Rees (1987) and Piran & Nakamura (1987) suggested that this might have been a relativistic jet generated by supernova. The new analysis of SN1987A data provided stronger evidence for the original "mystery spot" and in addition a second spot on the opposite side of the supernova, suggesting relativistic jets (Nisenson & Papaliolios 1999). Based on this, Paczyński (1999) suggests that there may be a broad range of the SN jet velocities, and some may perhaps be capable of GRB-like emission. We think that the key problem lies in how the untra-relativistic jets required for GRBs can be formed in the SN explosions. As we know, the SN has a massive envelope of mass at least $\sim 1M_{\odot}$; So, even the jet produced is collimated into a rather small cone $\frac{\Omega}{4\pi} \sim 10^{-3}$, it can only move with a mildly relativistic velocity ($\sim 0.8c$). In this Letter, we propose that the ultra-relativistic jet(s) can be formed in the following way: the newborn, massive neutron star formed in the SN explosion converts to a strange star in quite a short time (~ 1 days) as it spins down and this phase transition process

(Cheng & Dai 1996) and/or the differential rotation process of the newborn strange star (Dai & Lu 1998) can produce an ultra-relativistic ($\Gamma_0 \geq 100$) fireball, which subsequently produces a GRB. Because in this case the GRBs can occur only few days after the SN explosion, the SN-GRB connection can be naturally explained.

Neutron stars are known to be composed of neutrons and protons. In conditions of extremely high density, the smaller constituents (quarks) inside the protons and neutrons may have been deconfined. Since the strange matter is conjectured to be the true ground state (Bodmer 1971; Witten 1984) and its existence is allowable within uncertainties inherent in a strong-interaction calculation (Jaffe & Farhi 1984), a new phase of matter (strange quark matter) can occur. Strange stars, composed of this kind of quark matter, have been used to explain some astronomical phenomena (e.g. Cheng et al. 1998; Cheng & Dai 1998; Xu et al. 1999), although some arguments against the existence should also be kept in mind (e.g. Caldwell & Friedman 1991; Kluźniak 1994). The conversion of a neutron star to a strange star may require the formation of a strange matter seed, which is produced through the deconfinement of neutron matter at a density (Baym 1991) of $\sim 7-9\rho_0$ (where ρ_0 is the nuclear matter density), much larger than the central density of a $1.4M_\odot$ neutron star with a moderately stiff to stiff equation of state(EOS). The direct criterion for the conversion is that the total mass of the preconversion neutron star should exceed $1.8M_\odot$, if the EOS at high density is moderately stiff or stiff (Cheng & Dai 1996; Dai & Lu 1998).

2. ULTRA-RELATIVISTIC JET FROM THE STRANGE STAR AS GRB

Let us consider a massive progenitor with mass greater than $20M_\odot$ on the main sequence that undergoes a Type Ib/c or Type II supernova explosion and leaves a rapidly rotating neutron star with mass about $1.8-2.1M_\odot$. (But, for very massive progenitors with masses larger than $30M_\odot$, the collapsing iron cores may possibly implode to black holes rather than neutron stars before the explosions develop, which is just the "collapsar" model (MacFadyen & Woosley 1998; Woosley et al. 1999b) of γ-ray bursts.) Static neutron star with such a large mass may have undergone phase transition to become a strange star, but for a very rapidly rotating one (close to the break-up angular speed) (Cook et al. 1994), its central density may be much lower than the deconfinement density. Indeed, for moderately stiff EOSs, rapid rotation can sustain an extra mass up to $0.3M_\odot$ for a given central density. However, due to the rapid loss of angular momentum through magnetic dipole radiation, the newborn, massive neutron star spins down and its central density become larger and larger and finally converts to a strange star. To illustrate clearly, we give an example from the computation of Cook et al. (1994). For the modern EOS named FPS (Lorenz et al. 1993), the maximum angular velocity of a $1.8629M_\odot$ (gravitational mass) neutron star is $\omega = 0.88749 \times 10^4 \mathrm{s}^{-1}$. The corresponding central density is $\rho_c = 1.4835 \times 10^{15}$ g cm^{-3}. When it spins down to $\omega = 6.2200 \times 10^3 \mathrm{s}^{-1}$, its central density is $\rho_c = 2.2399 \times 10^{15}$ g cm^{-3}, reaching the deconfinement density of neutron matter.

Modelling of the optical light curve of SN1998bw shows that the time of core collapse coincides with that of GRB980425 to within (+0.7, -2.0) days (Iwamoto et al. 1998). This means that the spin-down time scale of the rapidly rotating neutron star (in fact it is a strongly magnetized millisecond pulsar) should not exceed two days, i.e. $T = \omega/\dot{\omega} \sim Ic^3/B^2R^6\omega^2 \leq 2$ days, where I, B and R are, respectively, the moment of inertia, magnetic field strength and stellar radius of the neutron star. If taking $I_{45}^{\frac{1}{2}}R_6^{-3} \sim 1$ (I_{45} is the moment of inertia in 10^{45}g cm^2 and R_6 is the stellar radius in 10^6cm), the magnetic field strength is required to be $B \geq 3.9 \times 10^{13}$ Gauss. For a newborn neutron star, it is a reasonable value.

Once the deconfinement density is reached, strange matter seeds are formed in the interiors of the star and the strange matter will begin to swallow the neutron matter in the surroundings. The conversion should proceed in a detonation mode (Lugones et al. 1994) (at a speed of sound) and the timescale for the conversion is about 0.1 millisecond. Although neutron star is composed of outer crust, inner crust and core, only the outer crust will not convert into strange matter because it does not contain free neutrons. Then the resulting strange star has a thin crust with mass $M_0 \sim 2 \times 10^{-5}M_\odot$ (Glendenning & Weber 1994; Huang & Lu 1997). It has been pointed out (Cheng & Dai 1996) that the energy deposition of this phase transition is mainly through the process of $n+\nu_e \rightarrow p+e^-$ and $p+\bar{\nu}_e \rightarrow n+e^+$ and the phase transition energy released (E_0) is of the order of 10^{52} ergs. The process, $\gamma\gamma \leftrightarrow e^+e^-$, will inevitably lead to the creation of a fireball, which expands outward, carrying the baryonic matter in the thin crust of the strange star. Finally, an ultra-relativistic shell is formed with a high Lorentz factor

$$\Gamma_0 \sim \frac{E_0}{M_0 c^2} \sim 300(\frac{E_0}{10^{52}\mathrm{ergs}})(\frac{M_0}{2\times 10^{-5}M_\odot})^{-1}. \tag{1}$$

In addition, there's also another important process that could sometimes act as the central engine of GRBs after the birth of the strange stars: differential rotation may occur in the interiors of these newborn strange stars due to the fact that the density profile of a strange star is much different from that of a neutron star with the same mass (Glendening 1997). According to the basic idea of the Kluźniak & Ruderman (1998), Dai & Lu (1998) argued that such differentially rotating strange stars could lead to a series of subbursts of GRBs by the following mechanism: In a differentially rotating strange star, internal poloidal magnetic field will be wound up into a toroidal configuration and linearly amplified as one part of the star rotates about the other part. Only when it increases up to a critical field value, will the toroidal field be sufficiently buoyant to overcome fully the stratification in strange star composition. And then the buoyant magnetic field will be able to float up to break through the stellar surface. Reconnection of the newborn surface magnetic field will lead to a quickly explosive event with a large amount energy, which could be a subburst of a GRB. It is worth emphasizing that there's no baryonic contamination problem in the fireball formed in these two scenarios due to the low mass of the crust of strange stars.

Can this ultra-relativistic shell(s) produce a detectable γ-ray burst inside the dense ejecta of supernova? It depends on the scattering optical opacity of ejecta. The scattering optical depth is $\tau = \sigma_T n l \sim 9.4(M_{ej}/M_\odot)(t/10\mathrm{days})^{-2}(v/3\times 10^9\mathrm{cm\ s^{-1}})^{-2}$. For Type II supernova with a ejecta of mass greater than $10M_\odot$, τ is less than unity about 100 days after the explosion. Since the rise time of Type II supernova is quite long, we think that if the time of core collapse is more than 100 days earlier than that of the phase transition, the γ-ray burst resulting from the fireball shock can then be detected. This may apply to GRB980326 and GRB970228, as the Types of SNe associated with them are unknown. Since in this case, the corresponding distance that the ejecta has reached is not large ($\sim 1-3\times10^{16}$cm), the fireball shock will definitely run into the dense ejecta not long after the burst and transit to a non-relativistic expansion regime (M*észá*ros et al. 1998; Dai & Lu 1999a,b), leading to a steeply decaying or even non-detectable afterglow, very similar to the "SupraNova" model (Vietri & Stella 1998) of γ-ray bursts. This agrees with the observations of GRB980326, whose optical afterglow decays as $t^{-2.1}$ (Bloom et al. 1999). Recent analysis (Galama et al. 1999) of the optical and near-infrared afterglow of GRB970228 also shows a steep temporal decay ($F_\nu \propto t^{-1.73}$). On the other hand, the rise time of Type Ib/c supernova is much shorter (∼2—3 weeks). So, even at the time that the luminosity of the supernova begins to decline, the scattering optical depth is still much greater than unity and no significant amount of gamma-rays can escape, unless there is a hole in the ejecta, which in fact implies a highly asymmetric supernova explosion. This scenario (involving a highly asymmetric supernova explosion) is the more likely case, since a Type Ib/c supernova SN1998bw has already been identified to be associated with GRB980425. Next we will discuss it in more detail.

In their models to explain the SN/GRB connection, Wang & Wheeler (1998), Cen (1998) and Nakamura (1998) assumed that the highly asymmetric explosion of Type Ib/c supernova makes the material in a small cone of the supernova ejecta be preferentially first blown out of the deep gravitational potential well of the star. Immediately (about a few seconds after the explosion), a tightly collimated jet from the core collapse rushes through the preferred "hole" and becomes an ultra-relativistic jet after an expansion phase. However, because the preexpelled material may still run in the direction of the small cone, we speculate that the fireball jet formed *immediately* after the explosion should be slowed down (viz. $\Gamma_0 \ll 100$) by the material before the fireball itself becomes optically thin, and difficult to produce a γ-ray burst. (Anyway, the mass in the small cone is about $10^{-3}M_\odot$ even for $\frac{\Omega}{4\pi}\sim10^{-3}$.) But we think that this process may accelerate the preexpelled material in the small cone ($\frac{\Omega}{4\pi}\sim10^{-3}$) to mildly relativistic velocity ($\sim 0.8c$) and leaves a preferred exit for the fireball formed *a few days later* by the conversion of a newborn neutron star to strange star or from the differentially rotating strange star. In this case, the fireball jet can reach a radius larger than 10^{16}cm and produce a γ-ray burst before catching up with the preexpelled material. In fact, there are some observational and theoretical evidences favouring the existence of mildly relativistic jet in the supernova explosion: 1)The mysterious spot in SN1987A which appeared $5-7$ weeks after the explosion at ~ 0.06 arc-second away from the center, implies a relativistic velocity (Rees 1987; Piran & Nakamura 1987) of $v \simeq (0.6 \pm 0.15)c/\sin\alpha$, where α is the angle between the velocity and the line of sight; 2) General relativistic numerical simulations (Piran & Nakamura 1987) have demonstrated that collapse of the rapidly rotating core bounces along the rotation axis to form jets moving with mildly relativistic velocity; 3)Superstrong magnetic field formed immediately after the core collapse is claimed to be able to punch a hole in the supernova ejecta and the preexpelled jet can also reach a relativistic velocity (Nakamura 1998). Moreover, because the newborn rapidly rotating neutron star may have a strong magnetic field, the energy released through the magnetic dipole radiation can be as large as $\dot{E} \sim B^2R^6\omega^4/c^3 \sim 4\times10^{46}\mathrm{ergs\ s^{-1}}(B/10^{13}\mathrm{G})^2(R/10^6\mathrm{cm})^6(\omega/10^4\mathrm{s^{-1}})^4$. Since a large fraction of this energy will be converted to photons, the ensuing luminosity in fact exceeds the Eddington luminosity for a neutron star by about 8 orders of magnitude. This high energy flow and the inherent rotation of the ejecta(if the jet moves along the rotation axis) may maintain the emptiness of the "hole".

The untra-relativistic shell (or shells) produced by the phase transition or/and from the differentially rotating strange stars will rush through the "hole" in the supernova ejecta and becomes jet-like. For the case that only the phase transition occurs, the γ-ray burst is more likely to be produced by the external shocks rather than internal shocks because the conversion of neutron stars to strange stars is very quick and the energy deposition is impulsive. The jet expands outward in a way similar to a homogeneous fireball, sweeping up more and more external matter. External shocks will occur when the observer-frame energy of the swept-up external matter($\Gamma^2 m_p c^2$ per proton) equals the initial energy of the fireball jet at a radius (M*észá*ros 1999)

$$r_{dec} \sim 2\times10^{16}\ \mathrm{cm}\ (\frac{E_{iso}}{10^{52}\mathrm{ergs}})^{1/3}(\frac{\Gamma_0}{300})^{-2/3}(\frac{n}{1\ \mathrm{cm}^{-3}})^{-1/3}, \tag{2}$$

where E_{iso} is the assumed isotropic energy of the jet ($E_{iso} = E_0$) and n the ambient density. The duration of the GRBs in the observer's frame is

$$\Delta t \sim \frac{r_{dec}}{\Gamma_0^2 c} \sim 10 \text{ s } (\frac{E_{iso}}{10^{52}\text{ergs}})^{1/3}(\frac{\Gamma_0}{300})^{-8/3}(\frac{n}{1 \text{ cm}^{-3}})^{-1/3}. \tag{3}$$

This time scale is in good agreement with the durations of the bursts which are thought to connect with supernovae. Variability on time scales shorter than Δt may occur on the cooling time scale of electrons or on the dynamic scale for inhomogenities in the external medium, but generally this is not ideal for reproducing highly variable profiles. Therefore, in this case we will generally see bursts with simple profiles, agreeing well with GRB980425 and GRB980326 (Soffitta et al. 1998; Celidonio et al. 1998). On the other hand, for GRB970228 that have a relatively complex time structure, we think it may be produced by internal shock resulting from the differentially rotation process of the newborn strange star, in which the faster shells catch up and collide with the slower ones.

Since the opening angle of the ultra-relativistic jet is always rather small ($\theta_j \sim 0.1$), the transition of its evolution from the spherical-like phase to the sideways-expansion phase will occur at a very early time $t_\oplus \sim 6$ hours $(\theta_j/0.1)^{8/3}(E_{iso}/10^{52}\text{ergs})^{1/3}(n/1 \text{ cm}^{-3})^{-1/3}$, where $t_\oplus$ is the time since the burst measured in the observer's frame (Sari et al. 1999). Therefore we will generally see rapidly decaying afterglows of the supernova-related γ-ray bursts. This gives a natural explanation of the rapid decay seen in the optical afterglows of GRB980326 ($F_\nu \propto t^{-2.1}$) and GRB970228 ($F_\nu \propto t^{-1.73}$) as well as the non-detection of their radio afterglows.

The major portion of the ultra-relativistic shell(s) will catch up and collide with the ejecta of the supernova that moves with a lower velocity and be immediately decelerated to a non-relativistic speed, heating the ejecta and producing super-Mev gamma-rays at the same time. However, no significant amount of gamma-rays can escape due to a high scattering optical depth of the dense ejecta, i.e. $\tau = \sigma_T n l > 1000$ (for the ejecta with $\sim 5M_\odot$) at the time two days after the explosion. Therefore, almost all of the energy of the fireball shell turns into the expansion energy of the massive ejecta, leading to a supernova with very bright optical luminosity and broad line emission, which are the very characteristics of SN1998bw. Note here that the unusually large explosion energy

($\sim 2-5\times 10^{52}$)erg (Woosley et al. 1999; Iwamoto et al. 1998) of SN1998bw associated with GRB980425 is remarkably close to the phase transition energy from a neutron star to strange star and should not be considered as a chance coincidence.

3. AFTERGLOW OF GRB980425

It is natural to think that the jet geometry (i.e. we observe this jet from the lateral direction) makes us detect a weak gamma-ray intensity of GRB980425 with an inferred energy only about 10^{48}ergs. Its weak optical afterglow emission is supposed to be suppressed by the luminous optical radiation of SN1998bw and therefore not seen by us. However when the radio afterglow dominates (we suggest the radio emission is from the afterglow of GRB980425 rather than SN1998bw), its emission angle $\theta \sim \frac{1}{\gamma} \sim \frac{1}{2}$ is quite large and at this time the observer may be inside this angle; hence, the radio emission we received should be bright, considering the short distance of the source from us.

Li & Chevalier (1999) modelled the radio light curve and inferred that the rise observed at days $20-40$ is due to the energy input from a central engine, favoring the connection between GRB980425 and SN1998bw. It is interesting to consider that the central engine may possibly be the newborn strange star which gives out the magnetic dipole radiation and that the decline-rise-decline light curve can be explained in a similar way as GRB970508 (Dai & Lu 1998). Since the newborn strange star should not be very different from the preconversion neutron star in the angular velocity and the magnetic field strength, it may also be a strongly magnetized millisecond pulsar, which radiates electromagnetic waves with frequency $\omega \leq 10^4\mathrm{s}^{-1}$. These waves are absorbed by the shocked interstellar medium(ISM) because the plasma frequency of the shocked ISM is much higher than ω. Based on energy conservation, the shocked ISM energy $4\pi n m_p c^2\gamma^2 r^3$ should be equal to the sum of $\sim E_{iso}/2$ and the energy from the pulsar:

$$4\pi n m_p c^2\gamma^2 r^3 = \frac{E_{iso}}{2} + \int_0^t (1-\beta)L(t-r/c)dt, \quad (4)$$

where $r \simeq c\,t$ is the blast wave radius measured in the burster's rest frame, γ the Lorentz factor of the blast wave, L the magnetic dipole radiation power and $\beta = (1-1/\gamma^2)^{1/2}$.

At the initial stage, the second term on the right side of Eq.(4) can be neglected and the radio flux declines in a usual way. Once the second term dominates, which is quite plausible since the rotation energy of the rapidly rotating strange star is comparable to the initial shock energy, the shocked ISM energy increases with time significantly, leading to the rise phase in the light curve. Finally, after the spin-down time scale of the strange star, the magnetic dipole radiation power decreases rapidly as $L \propto t^{-2}$. Hence, the energy input from the pulsar can be neglected again and the flux will decline.

4. DISCUSSIONS

We have proposed a model to explain the puzzling SN/GRB connection, based on the conversion of a newborn, massive neutron star to a strange star few days after the supernova explosion. We think that the untra-relativistic shell(s) responsible for GRBs could not be produced by the supernova itself, but possibly by the phase transition process or the differentially rotation process of the newborn strange star. The formation of a strange star requires that the total mass of the preconversion neutron star should exceed $\sim 1.8M_{\odot}$. According to the numerical simulation (Woosley et al. 1999b), when supernova occurs, some matter may fail to achieve escape and fall back onto the neutron star. For example, as they show, if the kinetic energy at infinity is set to be about 1.2×10^{51}erg for a $25M_{\odot}$ presupernova star, about $0.48M_{\odot}$ matter falls back onto the neutron star in about 1000 seconds. Therefore, it is reasonable to believe that some supernova explosions, especially for the progenitors with moderately massive mass (perhaps in the range $20 - 30M_{\odot}$), could produce massive neutron stars. But, for very massive progenitors (perhaps with mass higher than $30M_{\odot}$), it is very likely that more than $1M_{\odot}$ matter falls back and then the massive neutron star will promptly collapse to a black hole, which is just the subject of the "collapsar" model of GRBs or the two-step model (Cheng & Dai 1999) of GRBs associated with supernovae.

Our scenario has three clear features or predictions. First, a strange star, rather than a black hole or neutron star, is left after a SN/GRB event. Second, as the major part of fireball shell collides with the supernova ejecta, most of the energy (on the order of

10^{52}ergs) released in the conversion will finally turn into the kinetic energy of the ejecta, therefore the supernova should be very bright and show broad emission lines. Finally, the afterglows of supernova-related γ-ray bursts in this scenario will generally decay faster than usual ones as the result of beaming or dense medium.

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